Chapter 3 Nuclear Energy

3.1 Nuclear fission and fusion

A Nuclear fission

1 ______________________________ is a reaction in which

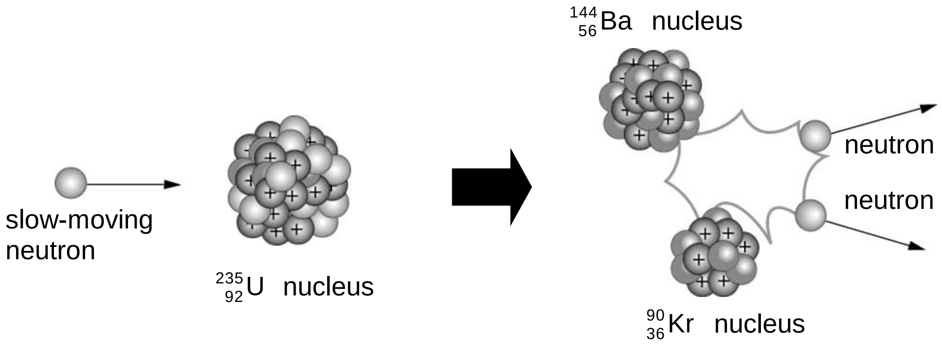
(a) a heavy nucleus splits into two or more lighter nuclei;

(b) a huge amount of _______________ is released;

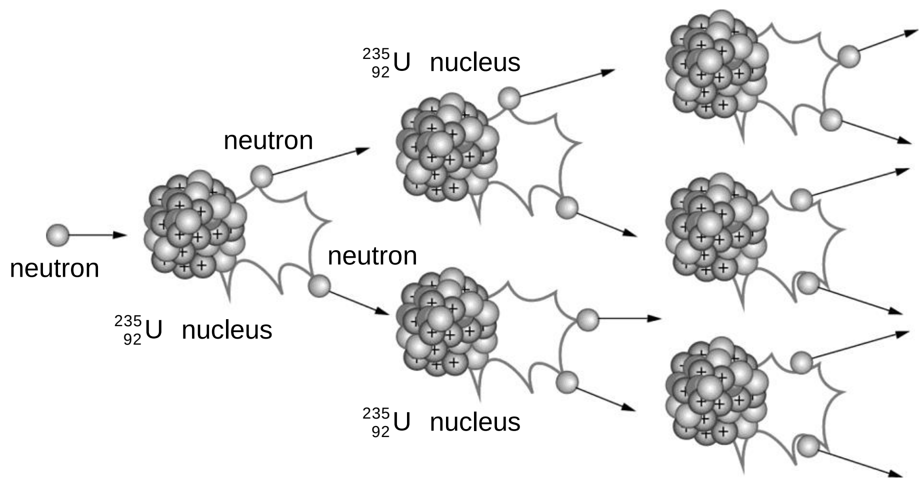
(c) _______________ are usually emitted.

2 Some nuclides undergo fission when they are bombarded by a _______________. For example, a uranium-235 nucleus can split in several ways when bombarded by a _______________________ neutron. The following gives one possible reaction:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{144}_{56}\mathrm{Ba} + ^{90}_{36}\mathrm{Kr} + 2^{1}_{0}\mathrm{n} + \text{energy}$$



3 The _______________ emitted in the fission of a uranium-235 nucleus can continue splitting other nearby uranium-235 nuclei. When the emission of neutrons and the splitting of nuclei continue in this way, _______________________ occurs.



4 The neutrons emitted in the fission may also ______________ without splitting any nuclei. However, if the amount of uranium-235 nuclei is _____________ enough, only small proportion of the neutrons will escape and the chain reaction can be sustained.

A chain reaction of uranium-235 is sustained if at least _______________ neutron from each fission splits another uranium-235 nucleus. The minimum amount of uranium-235 required for a sustained chain reaction is called the ______________________.

Checkpoint 1

In the following fission, *P*, *Q* and *R* denote different nuclei and *n* denotes a neutron. If a large amount of *P* nucleus is provided, can this fission result in a chain reaction?

$$P + n \longrightarrow Q + R$$

Solution

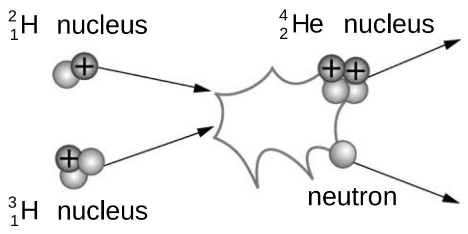
This fission is triggered by ______________, but it ________________________________.

Therefore, it ______________ (can / cannot) result in a chain reaction.

B Nuclear fusion

1 ____________________________ is a reaction in which two light nuclei join together to form a heavier nucleus.

2 A huge amount of energy is released in nuclear fusion when the interacting nuclei belong to elements with ______________ atomic numbers. The following gives an example.



In this fusion of hydrogen, 1 g of fuel releases about 3.4×10^{11} J of energy, which is much ______________ than that released by nuclear fission.

3 A very ____________________________ (~ 10^7 °C) is needed for fusion to occur. The positively charged nuclei should possess very high _____________________ to overcome the strong electrostatic repulsion between them.

4 The sun undergoes ______________ of hydrogen in its core to produce energy.

Ext 3.2 Mass-energy relationship

A Units of mass and energy in atomic scale

1 The ______________________________ (u) is a unit of mass, which is defined as:

$$\mathbf{1\ u} = \frac{\mathbf{1}}{\mathbf{12}} \times \textbf{mass of a } \underline{\hspace{6cm}}$$

$$= \underline{\hspace{5cm}}\ \mathbf{kg}$$

2 The table shows the masses of some particles in atomic mass unit.

Particle	**Mass / u**
proton	1.007 276
neutron	1.008 665
electron	0.000 549
hydrogen-2 (deuteron) nucleus	2.013 553
hydrogen-3 (tritium) nucleus	3.015 500
helium-4 nucleus	4.001 506
uranium-235 nucleus	235.043 923

3 The ______________________ (eV) is a unit of energy, which is the energy gained by an electron when it is accelerated by 1 V.

1 eV = e × 1 V = _________________ C × 1 V = _________________ J

B Mass-energy equivalence

1 Einstein suggested that __________ and __________ are equivalent and interconvertible.

2 In a nuclear reaction, energy is released due to a loss in the total mass of the reactants. The amount of energy released is given by the __________________________________:

$$\boldsymbol{\Delta E} = $$

where ΔE is the amount of energy released in __________,

Δm is the loss in mass in __________,

c is the speed of light, i.e. 3.00×10^{8} m s^{-1}.

Checkpoint 2

(a) Find the amount of energy released if 1 g of mass is completely converted into energy. Give your answer in J.

(b) A certain mass is completely converted into an energy of 100 000 J. Find the mass.

Solution

Apply $\Delta E = \Delta mc^2$.

(a) $\Delta E =$

$\therefore$ The energy released is ______________________.

(b) $\Delta m =$

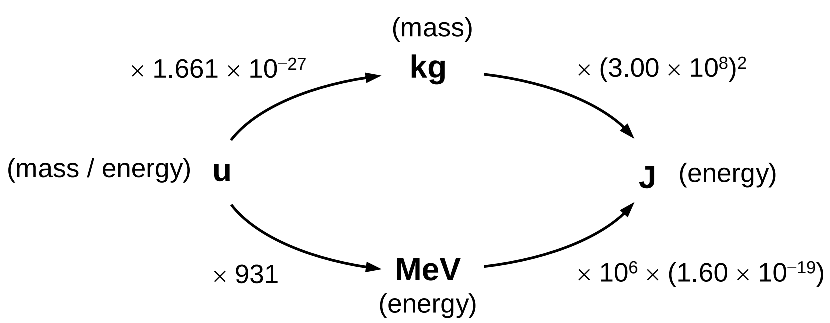
$\therefore$ The mass is ______________________.

3 The atomic mass unit can be used as a unit of _______________. For example, if the loss in mass in a reaction is 0.192 789 u, the energy released in the reaction can be simply expressed as 0.192 789 u. As a unit of energy,

1 u = ___________ MeV

* In calculation, unless otherwise specified, write any result in u correct to 6 decimal places.

4 The conversion between mass and energy in different units can be summarized as follows:



Checkpoint 3

Find the amount of energy that 2.05×10^{-28} kg of mass is equivalent to. Give your answer in (a) u, (b) J, (c) MeV.

Solution

(a) Energy =

(b) Energy =

(c) Method 1 ($\rightarrow$ u $\rightarrow$ MeV):

Energy =

Method 2 ($\rightarrow$ J $\rightarrow$ MeV):

Energy =

5 The amount of energy released in a nuclear reaction can be found as follows:

(a) Find out the mass of each particle involved in the reaction.

(b) Calculate the difference in the total mass of the particles before and after the reaction.

(c) Convert the mass difference into energy.

Checkpoint 4

The following equation shows the fission of uranium-235.

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + k\,^{1}_{0}\mathrm{n}$$

Given: mass of $^{235}_{92}\mathrm{U}$ = 235.043 923 u

mass of $^{141}_{56}\mathrm{Ba}$ = 140.914 403 u

mass of $^{92}_{36}\mathrm{Kr}$ = 91.926 173 u

mass of $^{1}_{0}\mathrm{n}$ = 1.008 665 u

(a) Find k.

(b) Find the energy released. Give your answer in J.

Solution

(a) Consider the ______________________.

(b) Total mass before reaction =

Total mass after reaction =

Loss in mass Δm =

Energy released $\Delta E = \Delta mc^2$ =

Checkpoint 5

A bismuth-210 (${}^{210}_{83}\text{Bi}$) nucleus decays to a polonium-210 (${}^{210}_{84}\text{Po}$) nucleus by emitting a β particle. The half-life of bismuth-210 is 5.01 days. Take the mass of ${}^{210}_{83}\text{Bi}$ to be 209.984 121 u, the mass of ${}^{210}_{84}\text{Po}$ to be 209.982 874 u and the mass of β particle to be 0.000 549 u.

(a) Find the energy released E in the decay. Give your answer in J.

(b) At a certain moment, there is 1 g of bismuth-210 nuclei in a container. Estimate the power due to the β decays of these nuclei.

Solution

(a) Bismuth-210 undergoes a β decay as follows:

$${}^{210}_{83}\text{Bi} \longrightarrow {}^{210}_{84}\text{Po} + {}^{0}_{-1}\beta$$

E = loss in mass = ____

= ______________________ u

=

(b) Number of bismuth-210 nuclei (N)

$$= \frac{\text{total mass}}{\text{mass of each nucleus}} =$$

Decay constant k =

Power due to the β decays = number of β decay occurring in each second × E

= $(kN) \times E$

=

3.3 Applications of nuclear energy

A Nuclear power

1 The use of nuclear energy can help solve the world's future energy ___________ crisis and reduces the problems caused by the burning of _____________________.

2 In a nuclear power station, controlled nuclear ______________ (fission / fusion) is used to generate electricity.

3 Enriched uranium-235 is a commonly used nuclear fuel. It undergoes fission in the _____________________ and releases energy to heat up the water to produce steam. The steam then drives the turbine / generator to produce electricity.

4 Nuclear fission produces radioactive substances. A leakage of these substances will cause serious and long-lasting health and environmental problems.

5 After the reusable materials are extracted, the _____________________ with long half-lives should be sealed in steel containers and stored underground.

6 Nuclear power has long been a contentious issue. Some pros and cons are listed below.

(a) Pros:

(i) Oil and coal will very likely run out soon. Nuclear power is a solution to the energy shortage crisis.

(ii) Nuclear fuel is small in size and easy to ______________.

(iii) Nuclear fuel is in many cases cheaper than coal or oil for generating electricity.

(iv) Nuclear power stations produce much fewer _____________________ than coal- and oil-fired power stations.

(b) Cons:

(i) Future energy needs can be met by using ______________ energy sources.

(ii) The widespread use of nuclear energy will lead to the growth of __________ ______________.

(iii) Greenhouse gases are produced in preparing the nuclear fuels. Besides, hot water is discharged from nuclear power stations into the sea and causes _____________________.

(iv) A nuclear accident has extremely serious consequences.

(v) Handling and storing nuclear waste cause serious safety problems.

7 Nuclear fusion has advantages over nuclear fission in generating electricity, but making controlled nuclear fusion is still not a practical reality.

(a) Advantages:

(i) The fusion fuel (hydrogen-2) is plentiful in ____________, so its cost is low.

(ii) The fusion product (helium) is inert and ______________________.

(b) Difficulties:

(i) It is difficult to maintain the ______________________ (10^7 °C) required for fusion to occur.

(ii) No actual solid container can withstand such a high temperature. Special techniques must be used to hold the fusion fuel and the products.

Checkpoint 6

The following equation shows the fusion of hydrogen.

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$$

Given: mass of $^{2}_{1}H$ = 2.013 553 u, mass of $^{3}_{1}H$ = 3.015 500 u,

mass of $^{4}_{2}He$ = 4.001 506 u, mass of $^{1}_{0}n$ = 1.008 665 u.

(a) Find the energy released in this reaction. Give your answer in MeV.

(b) What is the minimum mass of $^{2}_{1}H$ required to produce 1×10^{23} MeV of energy? Give your answer in kg.

(c) Explain why this fusion is difficult to use in generating electricity.

Solution

(a) Energy released = loss in mass

= ____

= ____________________ u

=

(b) Minimum mass of $^{2}_{1}H = \dfrac{\text{total energy released}}{\text{energy released in one reaction}} \times \text{mass of } ^{2}_{1}H \text{ in each reaction}$

=

(c) ____ is required for the fusion to occur, but no actual solid container can withstand this.

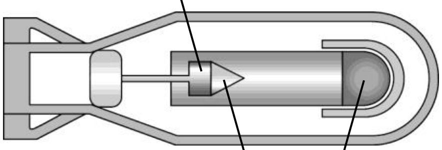
6 Ω

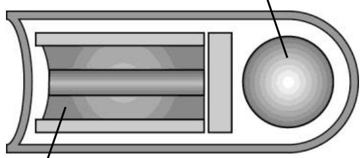
2 Ω

B Nuclear weapons

1 Nuclear weapons like ____________ bomb, ____________ bomb and ____________ bomb were developed from physics principles. Their great destructive power comes from ______________ (controlled / uncontrolled) fission or fusion.

2 The working principles of an atomic bomb and a hydrogen bomb are as follows:





Atomic bomb	Hydrogen bomb
Two lumps of fission fuel are forced together quickly. This makes the total mass exceed the critical mass and the uncontrolled nuclear fission occurs.	The atomic bomb explodes to provide a high temperature and trigger the uncontrolled nuclear fusion.

3 A neutron bomb is similar to the hydrogen bomb except that it explodes at high altitude. The ______________ produced in the nuclear fusion travel to the ground level and destroy life without affecting the ______________.